Why use electrons?

- Electron beam characteristics:
  - Rapid rise to 100%
  - Region of uniform dose
  - Rapid dose fall-off

Why use electrons?

- Tumors that can be treated with electrons
  - Superficial tumors
  - Lymph node boosts
  - Chest walls
  - CNS
  - TSI
Review electron interactions

- Long-range interactions with orbital electrons
  - Excitation and ionization
- Long-range interactions with atomic nuclei
  - Bremsstrahlung (x-rays)

Review electron interactions

- Characteristics of energy deposition
  - Continuous loss of energy – approx 2 MeV/cm (in water)
  - Multiple Coulomb scatter – spreading out of dose distribution at depth
- Electron interactions result in reductions in beam energy

Specification of electron energy

- \( (E_p)_0 \) (most probable energy at phantom surface)
- \( E_0 \) (mean energy at phantom surface)
- \( E_z \) (mean energy at depth \( z \))
Specification of electron energy

- \((E_p)_0\) – most probable energy at phantom surface
  \[
  (E_p)_0(\text{MeV}) = 0.22 + 1.98R_p + 0.0025R_p^2
  \]
- \(R_p\) – practical range (expressed in cm)

Specification of electron energy

- \(E_0\) – mean energy at phantom surface
  \[
  \bar{E}_0(\text{MeV}) = 2.33R_{50}
  \]
- \(R_{50}\) – depth at which dose is 50% of maximum dose (expressed in cm)

Specification of electron energy

- \(E_z\) – mean energy at depth \(z\)
  \[
  \bar{E}_z = \bar{E}_0 \left(1 - \frac{z}{R_p}\right)
  \]
- Note that energy decreases linearly with depth
Electron energy measurement

- Average Energy ($E_0$):
  \[ E_0 = 0.22 + 1.98 \times R_0 + 0.0025 \times R_0^2 \]

- Most Probable Energy ($E_{p0}$):
  \[ E_{p0} = \frac{E_0}{1 + 0.5 \times R_0} \]

- Energy ($E_z$) at depth $z$:
  \[ E_z = E_0 \left( 1 - \frac{z}{R_0} \right) \]

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>$E_{p0}$ (MeV)</th>
<th>$E_0$ (MeV)</th>
<th>$E_z$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>6.06</td>
<td>5.43</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>8.86</td>
<td>8.22</td>
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<td>12</td>
<td>12.11</td>
<td>11.46</td>
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<td>16</td>
<td>15.90</td>
<td>15.21</td>
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<tr>
<td>20</td>
<td>20.17</td>
<td>18.92</td>
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</table>

Properties of depth dose distributions

- Characterized by uniform irradiation to specified depth, followed by sharp fall-off

Clinical consequence

- Deliver uniform dose to superficial tumor (e.g., nodes, chest wall), with sparing of distal tissue
1. Shallow depths -- build-up region caused by side-scattered electrons
   - Surface dose increases with increase in energy

Increase surface dose with increased energy

- Lower energies
  - Electrons scattered through larger angles
  - Dose builds up more rapidly over shorter distance
  - Ratio of surface dose to maximum dose less
Increase surface dose with increased energy

- Higher energies
  - Electrons scattered through smaller angles
  - Dose builds up more slowly over longer distance
  - Ratio of surface dose to maximum dose greater

Regions of electron depth dose distributions

2. Region of sharp dose falloff begins at approximately 90% dose

Region of sharp dose falloff

- Select electron energy so that 90% or 80% isodose encloses target volume
Region of sharp dose falloff

- Depth of 80% central-axis dose easy to estimate:
  \[ d_{80}(\text{cm}) = \frac{1}{3} E(\text{MeV}) \].

Region of sharp dose falloff

- Depth of the 80% Dose:
  - Equal to approximately 1/3 nominal energy:
  - Depth of 90% is approximately 1/4 nominal energy

<table>
<thead>
<tr>
<th>( E_{\text{nominal}} ) (MeV)</th>
<th>( \frac{E_{\text{nominal}}}{3} )</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.0</td>
<td>1.99</td>
</tr>
<tr>
<td>9</td>
<td>3.0</td>
<td>3.08</td>
</tr>
<tr>
<td>12</td>
<td>4.0</td>
<td>4.26</td>
</tr>
<tr>
<td>16</td>
<td>5.3</td>
<td>5.70</td>
</tr>
<tr>
<td>20</td>
<td>6.7</td>
<td>6.96</td>
</tr>
</tbody>
</table>

- Depth of 80% is approximately 1/4 nominal energy

Region of sharp dose falloff

- Slope of falloff becomes more gradual with increasing energy
Regions of electron depth dose distributions

3. At end of falloff region, beyond range of electrons, tail is due to bremsstrahlung

Region of bremsstrahlung tail

- Magnitude of tail increases with increasing energy
  - Typically around 5% of maximum dose

Region of bremsstrahlung tail

- X-Ray Contamination:
  - Increases with energy:
    | E (MeV) | X-ray % |
    |---------|---------|
    | 6       | 1.3%    |
    | 9       | 1.6%    |
    | 12      | 2.1%    |
    | 16      | 2.7%    |
    | 20      | 4.5%    |
  - Varies with accelerator design

X-ray %

Varian 2100C
Region of bremsstrahlung tail

- Practical range of electrons can be estimated using approximate relation:
  \[ R_p (\text{cm}) = \frac{1}{2} E(\text{MeV}). \]

Region of bremsstrahlung tail

- Practical Range:
  - Equal to approximately 1/2 nominal energy:
    - Energy loss is about 2 MeV / cm

<table>
<thead>
<tr>
<th>( E_{\text{nominal}} )</th>
<th>( E_{\text{nominal}}/2 )</th>
<th>( R_p )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3.0</td>
<td>2.97</td>
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<td>9</td>
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<td>7.95</td>
</tr>
<tr>
<td>20</td>
<td>10.0</td>
<td>10.09</td>
</tr>
</tbody>
</table>

Field-size dependence

- Note increase in penetration with field size until lateral equilibrium is reached.
**Choice of energy and field size**

- Choose field size and energy so that target volume lies entirely within 90% isodose curve
  - Need to provide sufficient margin to enclose target volume – base on isodose curves

**Oblique Incidence**

- Isodose lines track skin surface
- Central axis has approximately same depth dose as normal incidence beam

**Oblique Incidence**

- Modifications
  - Inverse square correction
  - Changes in side scatter
    - ↑ scatter at R_{100}
    - Shift R_{100} toward surface
    - ↓ beam penetration
Matching Fields

Max doses
100 MU 16 MeV e
- No gap - 147 cGy
- 1 cm gap - 103 cGy
- 0.5 cm gap - 120 cGy

Matching Fields

- Electron dose spreads with depth due to scattering ⇒ hot spots and/or cold spots in region of overlap, depending on amount of field separation

Matching Fields

- To mitigate problem: move electron field junction several times during course of treatment
  - Smears out hot and cold spots
Heterogeneities

• Affect central-axis depth dose – based on density-weighted depth
• Affect electron scatter

Heterogeneities

• Increase (decrease) in scatter from heterogeneity gives rise to hot and cold spots adjacent to heterogeneity boundary

Surface irregularities

• Produce hot and cold spots due to scatter
  – Force tapering using bolus
  – If bolus is used, edges should be tapered
Surface irregularities

- Another consequence: Surface irregularities or may cause high dose gradients in the vicinity of \( d_{100} \), making that point unsuitable for dose prescription.

Dose prescription

- How to prescribe dose, or 90% is 90% of what?
- Dose reference point is \( d_{100} \) for beam perpendicularly incident on water phantom at same SSD
  - This point is well-defined and in a region of low dose gradient

Monitor unit setting

- The monitor unit setting \( (U) \) on a linear accelerator is determined by the equation:
  \[
  U = \frac{D_{\text{max}}}{D_{\text{max}}/U}
  \]
**Given Dose Output (cGy MU⁻¹) – \( D_{max}/U \)**

- **Definition:** The given dose output is the dose per monitor unit to muscle delivered to a point on the central axis at depth \( d_{max} \) in a water phantom.

**Source of Data:** The given dose output is calculated using the formula:

given dose output = calibration dose output
\( \times \) output factor
\( \times \) inverse square factor
\( \times \) air gap factor
\( \times \) skin collimation factor

**Output Factor – \( OF(C_s,I_{eq}) \)**

- **Note:** This is for fixed cone applicators. Other formalisms hold for variable applicators.
- **Definition:** The output factor is the ratio of the output (dose per monitor unit) in water for an SSD equal to the source-isocenter distance and a depth equal to \( d_{max} \) on central axis for a specified cone and equivalent insert size to the calibration dose output.
**Output Factor – $OF(C_s, I_{eq})$**

- **Square root method** (used with almost all current electron linear accelerators, including all accelerators presently at MDACC):

$$\text{output factor} = \sqrt{\frac{\text{output factor}_{\text{length} \times \text{length}} \times \text{output factor}_{\text{width} \times \text{width}}}{2}}$$

$$OF(C_s, X_{iso} \times Y_{iso}) = \sqrt{OF(C_s, X_{iso} \times Y_{iso}) \times OF(C_s, Y_{iso} \times Y_{iso})}$$

**Inverse Square Factor - ISF**

- **Source of Data:** The inverse square factor is computed according to the following equation:

$$\text{inverse square factor} = \left[ \frac{\text{calibration output distance}}{\text{treatment output distance}} \right]^2$$

$$\text{ISF}(\text{SSD}, d_{\text{max}}) = \left[ \frac{SAD + d_{\text{max}}}{\text{SSD} + d_{\text{max}}} \right]^2$$

**Source-Skin Distance (cm) – SSD**

- **Definition:** The source-skin distance is the distance from the virtual radiation source to a point defined on the patient's skin surface, projected onto the central axis.

  - Note that virtual source position may not coincide with nominal source position.
  - Often nominal source position used to avoid confusion.
**Air Gap Factor – \( f_{air} \)**

- **Definition:** The air gap factor is the ratio of the output measured at a specified SSD to the inverse-square-predicted output for that SSD
  - It corrects for the loss of side-scatter equilibrium, collimator scatter, other scatter effects, and, when appropriate, utilization of a nominal SSD

\[ f_{air}(X_{iso}, Y_{iso}, g) = \left[ \frac{f_{air}(X_{iso}, X_{iso}, g) \times f_{air}(Y_{iso}, Y_{iso}, g)}{f_{iso}(X_{iso}, X_{iso}, Y_{iso}, Y_{iso}, g)} \right]^{\frac{1}{2}} \]

**Skin collimation factor – SCF**

- **Definition:** The skin collimation factor is a correction to the output factor that results from a shift of the \( d_{max} \) depth toward the patient surface that can occur when skin collimation is included in an electron field